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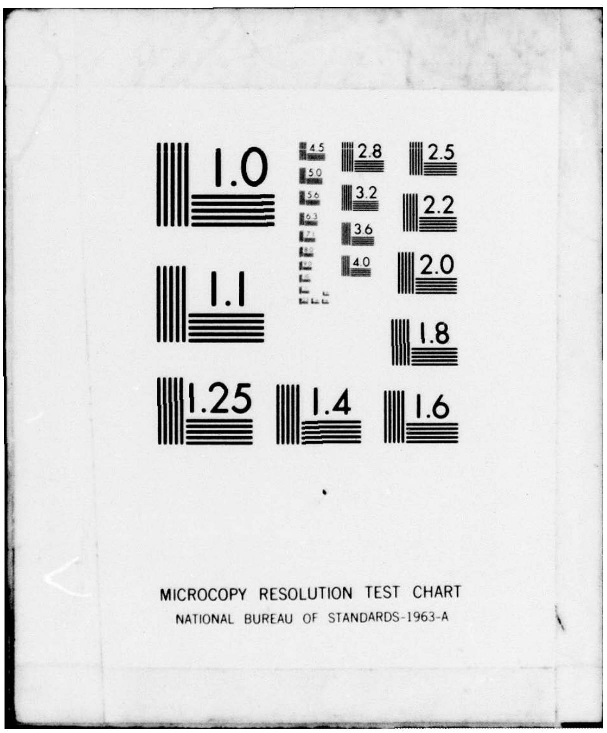
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OPTICAL CHANNEL WAVEGUIDE ARRAYS COUPLED TO INTEGRATED CHARGE-COUPLED DEVICES AND THEIR APPLICATIONS*

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Abstract

Device configurations of optical channel waveguide arrays coupled to integrated charge-coupled devices (CCDs) will be presented. Optical and electrical performance of these devices will be discussed. A channel waveguide array formed in a fan-out pattern is then introduced as a means of enhancing optical waveguide focal plane resolution in integrated optical devices utilizing optical waveguide lenses. High spatial resolution can thus be obtained without making detector spacings too small, thus avoiding detector problems with regard to fabrication, cross talk, linearity and —> to p. -B-

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Device configurations of optical channel waveguide arrays coupled to integrated charge-coupled devices (CCDs) will be presented. Optical and electrical performance of these devices will be discussed. A channel waveguide array formed in a fan-out pattern

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charge transfer efficiency. To fabricate the fan-out channel waveguide array, a new differential heating and photoresist lift-off process is discussed which allows high resolution patterns to be reproducibly formed in polyurethane. Propagation of light from a HeNe laser in these fan-out channel waveguide arrays has been demonstrated with only a small amount of scattering. Low scattering is consistent with the smooth channel waveguide surfaces apparent in scanning electron microscope pictures presented. Applications of optical channel waveguide arrays coupled to integrated CCDs to fiber multiplexing and transversal filtering will also be discussed.

Introduction

Integrated optical device configurations utilizing a silicon substrate have previously been discussed.[1] The motivation for investigating devices utilizing silicon is first, due to its potential use for such signal processing devices as the integrated optical spectrum analyzer,[2] second, its usefulness for performing waveguide detection in such signal processing devices formed on $LiNbO_3$, and third, to allow combination of integrated optical devices and integrated electronic circuits to form higher data rate systems. In the present paper we consider the integration of optical channel waveguide arrays integrated with charge-coupled devices (CCDs) and discuss some of the applications. Channel waveguides provide confinement of the propagating field in all transverse directions. When an array of channel waveguides is integrated with a CCD, each channel waveguide terminates onto a linear CCD imager array element. The CCD then multiplexes the information contained in the parallel optical channels, providing a serial electrical output.

As noted earlier one of our motivations for continuing to investigate integrated optical devices utilizing silicon substrates is to eventually allow the combination of integrated optical devices and integrated electronic circuits to form higher data rate systems. The basic integrated optical device in such systems is expected to be the channel waveguide. Fibers can readily be coupled to such channel waveguides using techniques demonstrated previously.[7,8] The coupling of arrays of fibers to arrays of channel waveguides should allow the transmission of information to silicon integrated circuits at much higher data rates than is possible with electrical connections.

Signal processing devices such as the integrated optical spectrum analyzer are motivating the development of integrated optical waveguide lenses.[2-5] The constraints of limited substrate area and high frequency resolution lead to the use of small f-number waveguide lenses. To fully resolve focal plane light distributions for such lenses, detector arrays having center-to-center spacings of a few microns are required. As system requirements point toward several hundred resolvable spots, use of a CCD linear imaging array is advantageous. Forming a CCD linear image array having a period of several microns is difficult but possible. However, as integrated optical devices such as the spectrum analyzer are expected to use a semiconductor laser having $\lambda = .82\mu m$, the absorption length in silicon is about $15\mu m$.[6] The fabrication of a CCD linear imaging array having a period significantly less than the absorption length, but in which channel isolation is to be maintained, adds considerable difficulty to the design and fabrication tasks. For these reasons we are presenting an alternate approach utilizing a channel waveguide fan-out array coupled to an integrated CCD. This device provides the desired fine spatial resolution, while allowing use of a CCD having a much larger period. The larger period simplifies CCD fabrication and provides improved channel isolation.

In what follows we shall introduce the device configurations of the channel waveguide arrays integrated with CCDs. Results concerning their optical and electrical performance will be discussed. Applications of the fan-out configuration to higher resolution imaging and fiber multiplexing and the straight channel device to transversal filtering will then be considered.

Device Configurations and Applications

The basic structure of a channel waveguide array coupled to an integrated CCD is shown in Fig. 1-a.[9] Another version with channel waveguides curved in a fan-out pattern for high resolution imaging is shown in Fig. 1-b. The channel waveguides in this structure are formed by first utilizing anisotropic etching of the (100) silicon surface, then thermally oxidizing the surface to form a layer of SiO_2, and finally filling the V-grooves with a suitable liquid which serves as the waveguiding medium.[10,11] Although this device utilizes anisotropic etching to form channel waveguides, an example of channel waveguide formation utilizing the photoresist lift-off process will be presented later. In Fig. 1 each channel waveguide terminates at a detector element where the SiO_2 region gradually disappears in order to effect coupling of light from the waveguide to the detector element.[12] As light enters each detector element, carriers are excited and collected under each respective isolated section beneath the integration gate shown in Fig. 1. At the end of an integration time, the transfer gate is turned on so that the accumulated charge is transferred in parallel into the CCD. The potentials of the various electrodes of the CCD are adjusted so that channel isolation is maintained during this parallel transfer. Once the transfer is accomplished the transfer gate is turned off and the charge packets are transferred along the CCD to the output where a multiplexed signal emerges. The procedure is then repeated.

The device shown in Fig. 1 has been fabricated with the result shown in Fig. 2. The CCD is a 4-phase device utilizing two levels of overlapping polycrystalline silicon electrodes and incorporates an MOS output reset amplifier. Charge transfer efficiency or inefficiency can be measured by serially injecting electrically a train of equal-amplitude pulses and noting degradation at the output.(13) Results of such measurements on the device in Fig. 2 is shown in Fig. 3. Defining charge transfer inefficiency as the fraction of charge lost per transfer, the results in Fig. 3 correspond to a transfer inefficiency of 1.0×10^{-4}. Details of array isolation and uniformity have been presented elsewhere.(9)

The optical Fourier transform system(2) for performing spectrum analysis of signals having bandwidths of the order of several hundred MHz is a prime example of both the developmental needs and the processing power of integrated optical signal processing systems. For such systems, as noted earlier, the constraints of limited subsection beneath the integration gate shown in Fig. 1. At the end of an integration time, the transfer gate is turned on so that the accumulated charge is transferred in parallel into the CCD. The potentials of the various electrodes of the CCD are adjusted so that channel isolation is maintained during this parallel transfer. Once the transfer is accomplished the transfer gate is turned off and the charge packets are transferred along the CCD to the output where a multiplexed signal emerges. The procedure is then repeated.

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The optical Fourier transform system(2) for performing spectrum analysis of signals having bandwidths of the order of several hundred MHz is a prime example of both the developmental needs and the processing power of integrated optical signal processing systems. For such systems, as noted earlier, the constraints of limited substrate area and high frequency resolution lead to the use of small f-number, short focal length waveguide lenses and detector arrays in the lens focal plane with center-to-center spacings of a few microns. We now consider a channel waveguide array configured in a fan-out pattern to collect light at the required resolution at the lens focal plane. The fan-out channel waveguide center-to-center spacing increases between the optical input end and the detector array end, thus detector array design and position are not controlled by the optical resolution requirements. This greatly simplifies detector array design and fabrication.

The actual fan-out array pattern, shown in Fig. 4, is computer generated. Program data includes center-to-center spacing and width of the channel waveguides at the input and output ends of the array, and the length of the array. The computer then generates the pattern on a flat bed plotter. The width of each channel increases linearly between the input and output ends. As each channel follows a sinusoidal path between input and the output, the spacing between guides gradually increases. The sinusoidal path is a half cycle in length so that the slope is zero at each end. This is to insure a straight waveguide for best sampling at the input, and alignment ease at the output. The curved channel waveguides shown in Fig. 4 have been designed so that the curvature is small enough to avoid scattering due to waveguide curvature.[14]

A channel waveguide array incorporating a fan-out pattern has been fabricated utilizing polyurethane to form the waveguides. Since the channel waveguides discussed earlier have been formed by dripping polyurethane onto V-groove areas of integrated optical electronic devices after packaging and wire bonding, there was little or no control over polyurethane spreading, uniformity or thickness. Channel waveguides formed in this way were characterized by the serious problem of light leakage from channel waveguides, since polyurethane also covered the area between V-grooves. A differential heating-lift off process discussed herein eliminates all these difficulties, and makes the V-groove formation optional, instead of essential to the creation of channel waveguide arrays. The process is thus applicable to substrate materials in which V-grooves cannot be formed. Using a positive photoresist, Shipley AZ1350J in this case, which can be stripped from the sample in a solvent, it has been possible to define metal patterns without acid etching using the lift-off technique.(15) Based on previous expertise of defining metal patterns in this way, polyurethane pattern definition by lift-off seemed possible. The final differential-heating and lift-off process exploits the curing properties, as well as the lift-off process, to yield 5 micron resolution of repeatable patterns in polyurethane. Better resolution may be possible, but mask-making and photoresist processing limitations of our laboratory prevented us from trying smaller geometries. Details of this process will be published elsewhere.(14)

Fig. 5a and 5b show scanning electron microscope (SEM) pictures of a typical device at the output end. Fig. 5a show several channels, which are uniform in size, surface and edge quality. Fig. 5b shows the edge quality in more detail. Fig. 6a and b similarly show the input end of the array. The spaces are very consistent and do extend down to the wafer surface. Some slight cross linking of channels does appear, but simultaneous exposure and development or preemphasis techniques, or just smaller waveguide duty cycles on the original mask would eliminate this. Optical microscope examination of these devices does not show edge quality or film thickness very well. The absence of color fringes confirms the uniform thickness, and the surface of good devices appears smooth optically. SEM pictures show a bit more edge and thickness detail, but due to the uniform flatness of the device, even quality SEM pictures are extremely difficult to obtain. This is a favorable indication of surface quality. Details concerning operation of these fan-out channel waveguide arrays will be published elsewhere.[14]

Channel waveguide structures coupled to integrated CCDs also present excellent potential for applications such as multiplexing or transversal filtering in which optical channels can replace electrical channels and thereby eliminate capacitive coupling and thus the inherent limitation on data rates in electrical channels. An example of a multiplexer configuration has been discussed in previous papers,[1,8] while a possible configuration of a transversal filter utilizing a channel waveguide array is shown in Fig. 7. The four MOS transistors are included to symbolize analog multiplication for establishing tap weights in the transversal filter. Weighting could be achieved in a number of ways; for example, pulse duration modulation of the light in each channel waveguide could readily provide programmable weighting.(16) The operation of the transversal filter in Fig. 7 is similar to usual transversal filter operation,(17) but for the fact that channel weighting occurs before variable channel delay. However, the resulting transfer function is not changed. The integrated optical channel waveguide transversal filter structure of Fig. 7 is expected to be superior to electrical structures because of the absence of capacitance coupling and to bulk optical structures(18) because it allows for greater channel isolation and density. This latter characteristic provides for more accuracy of the desired filter frequency response.

Summary

Device configurations of an array of optical channel waveguides coupled to an integrated CCD have been presented. For applications involving a waveguide lens such as integrated optical spectrum analysis, we have configured the channel waveguide array into a fan-out pattern. This fan-out array provides high resolution in the lens focal plane, with the channel waveguides spreading out in a fan-out pattern as they terminate on the elements of a detector array. Use of such an array circumvents the need to use a CCD with small element center-to-center spacing, thus alleviating problems with regard to line definition, CCD registration, and detector array crosstalk. The fan-out array concept is also flexible in that a standard detector array could be used for different resolution tasks simply by modifying the channel waveguide array input center-to-center spacing. The fan-out patterns actually fabricated utilized a new differential heating and photoresist liftoff process which allows high resolution patterns to be reproducibly formed in polyurethane. Application of integrated channel waveguide array-CCD configurations to transversal filtering and multiplexing has also been briefly discussed.

Acknowledgments

The authors wish to acknowledge contributions to this work by Dr. C. L. Chen. We further wish to thank J. T. Garrett for technical assistance, and E. Clark, J. Rodman, and S. Garg for assistance with SEM analysis.

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Figure 6b	SEM picture of individual space between waveguides and outer-most waveguide.
Figure 7	Schematic diagram of an integrated optical waveguide-CCD transversal filter.

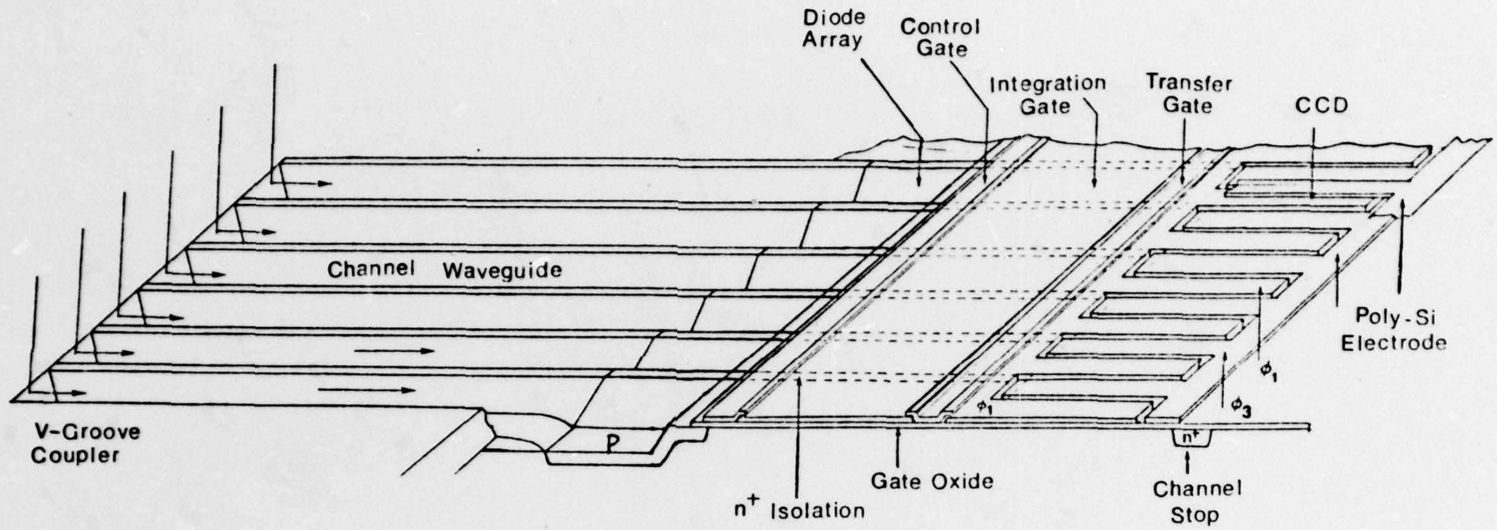

Figure 1a   Integrated channel waveguide array- CCD device configuration

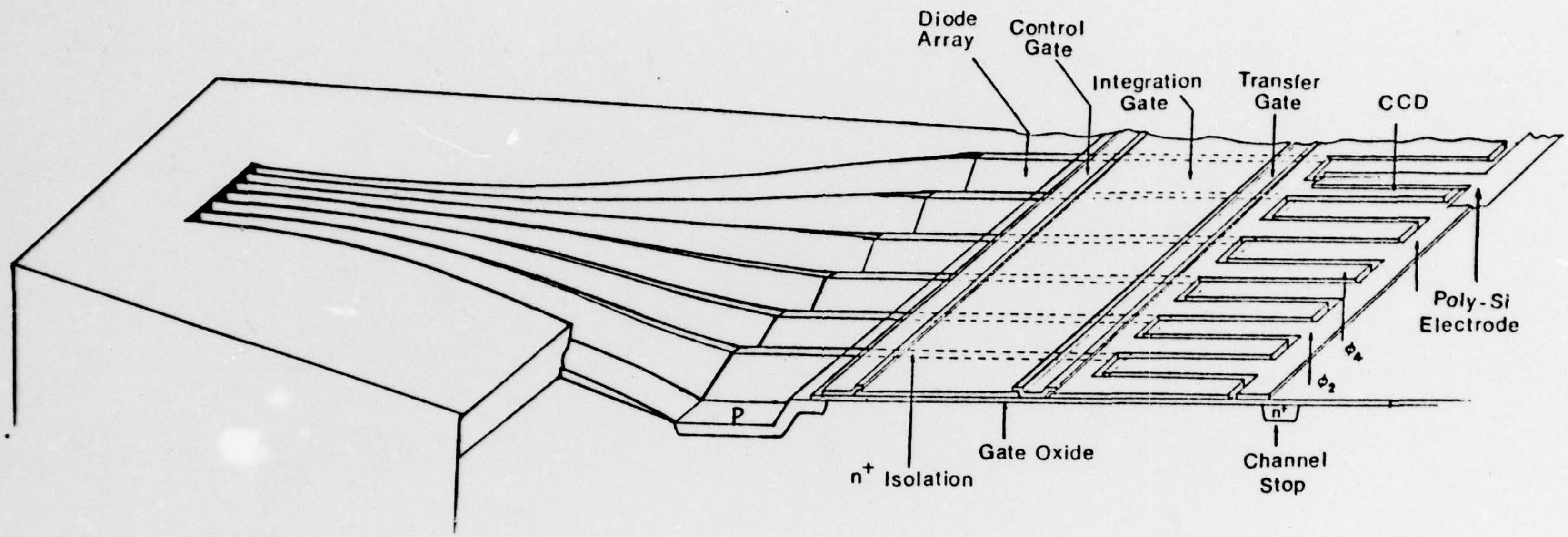

Figure 1b Same as in (a) but with waveguide array fan-out pattern.

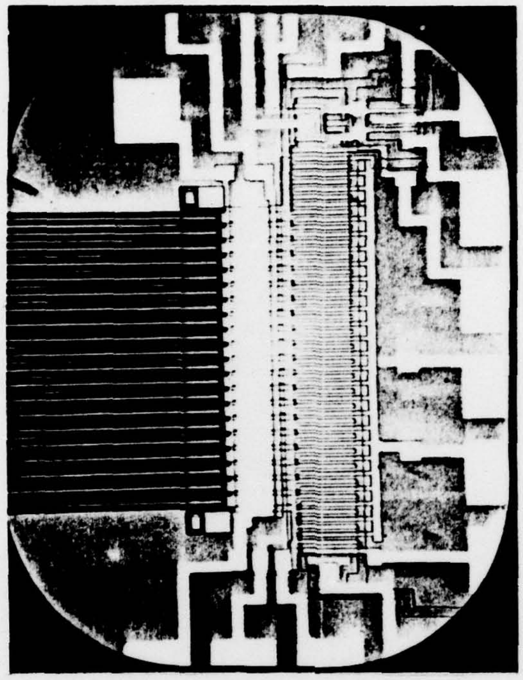

Figure 2 Photograph of device shown schematically in Fig. 1-a.

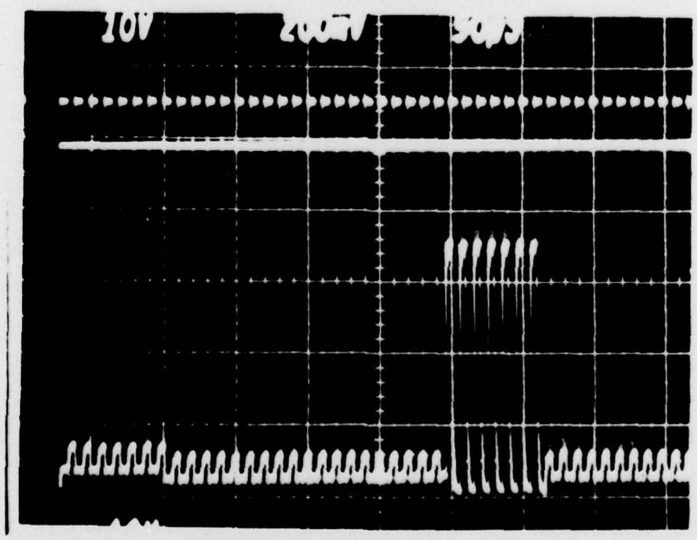

Figure 3 CCD output corresponding to serial input of a group of equal-amplitude pulses.

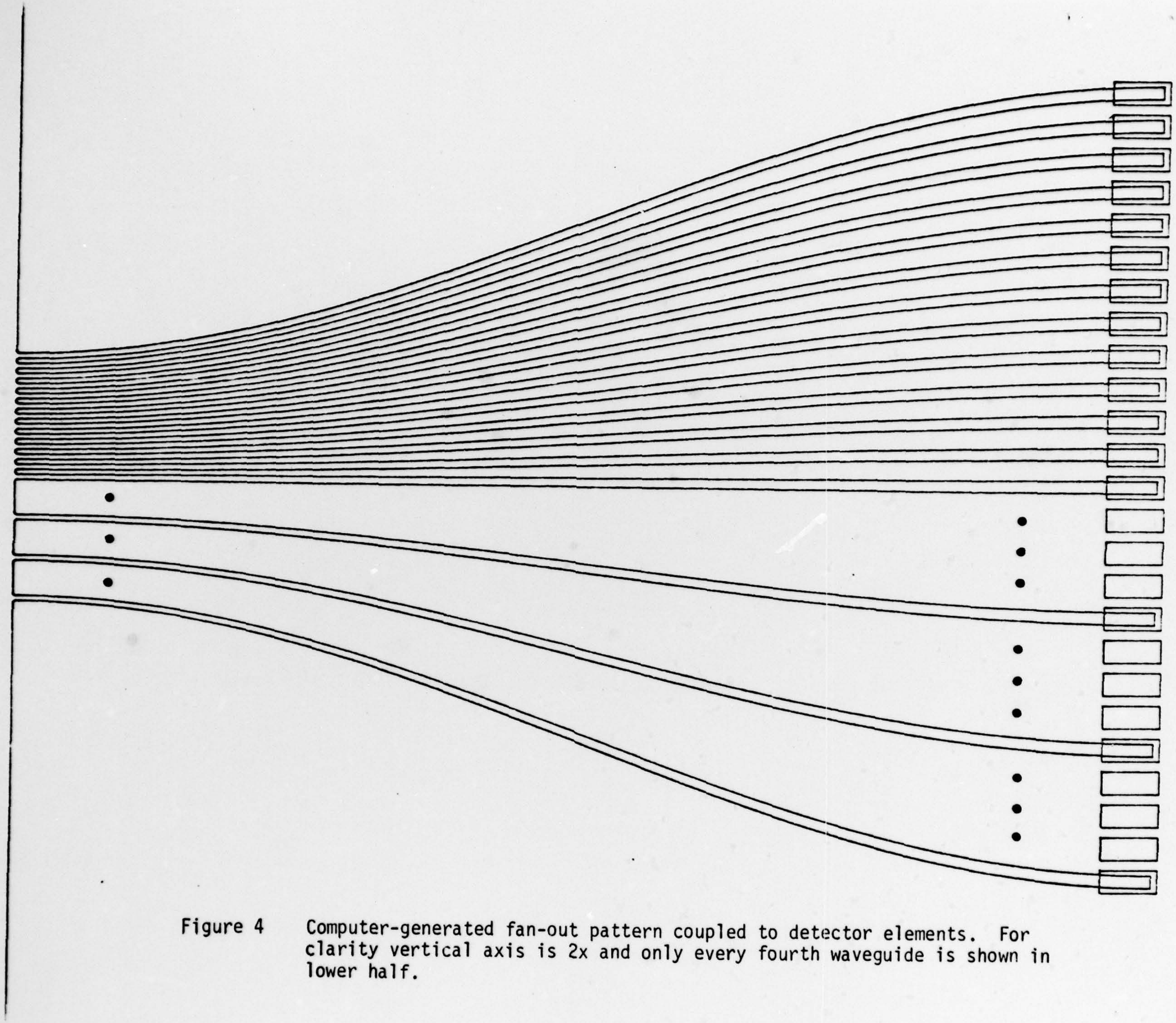

Figure 4 Computer-generated fan-out pattern coupled to detector elements. For clarity vertical axis is 2x and only every fourth waveguide is shown in lower half.

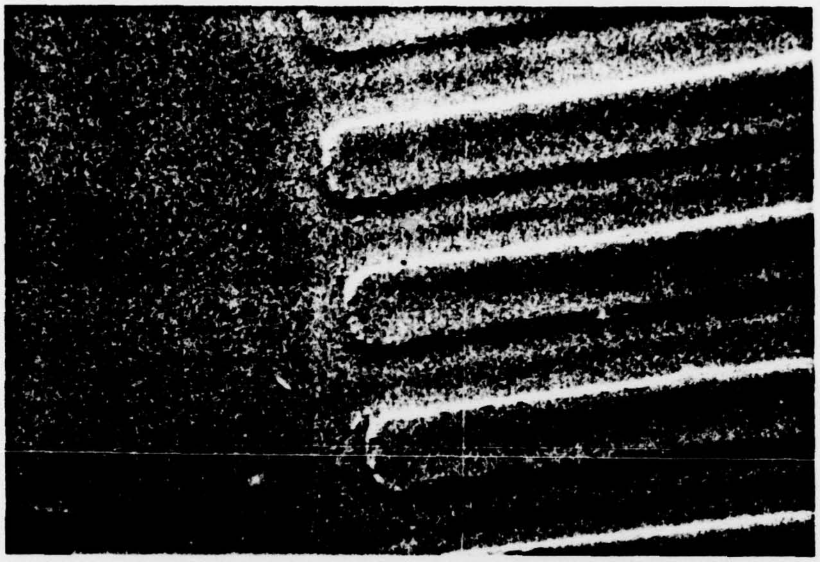

Figure 5a SEM picture of output end of several channel waveguides.

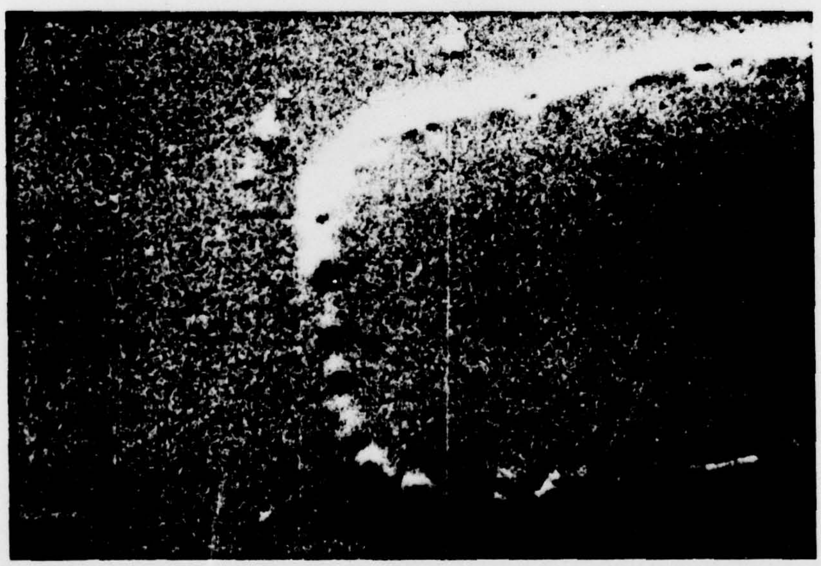

Figure 5b SEM picture of edge and surface of individual channel waveguide output end.

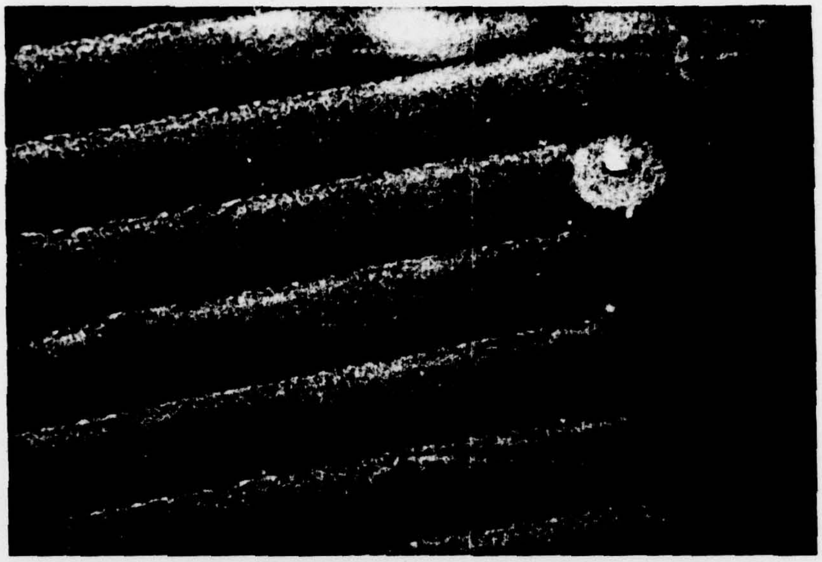

Figure 6a SEM picture of input end of fan-out array.

Figure 6b SEM picture of individual space between waveguides and outermost waveguide.

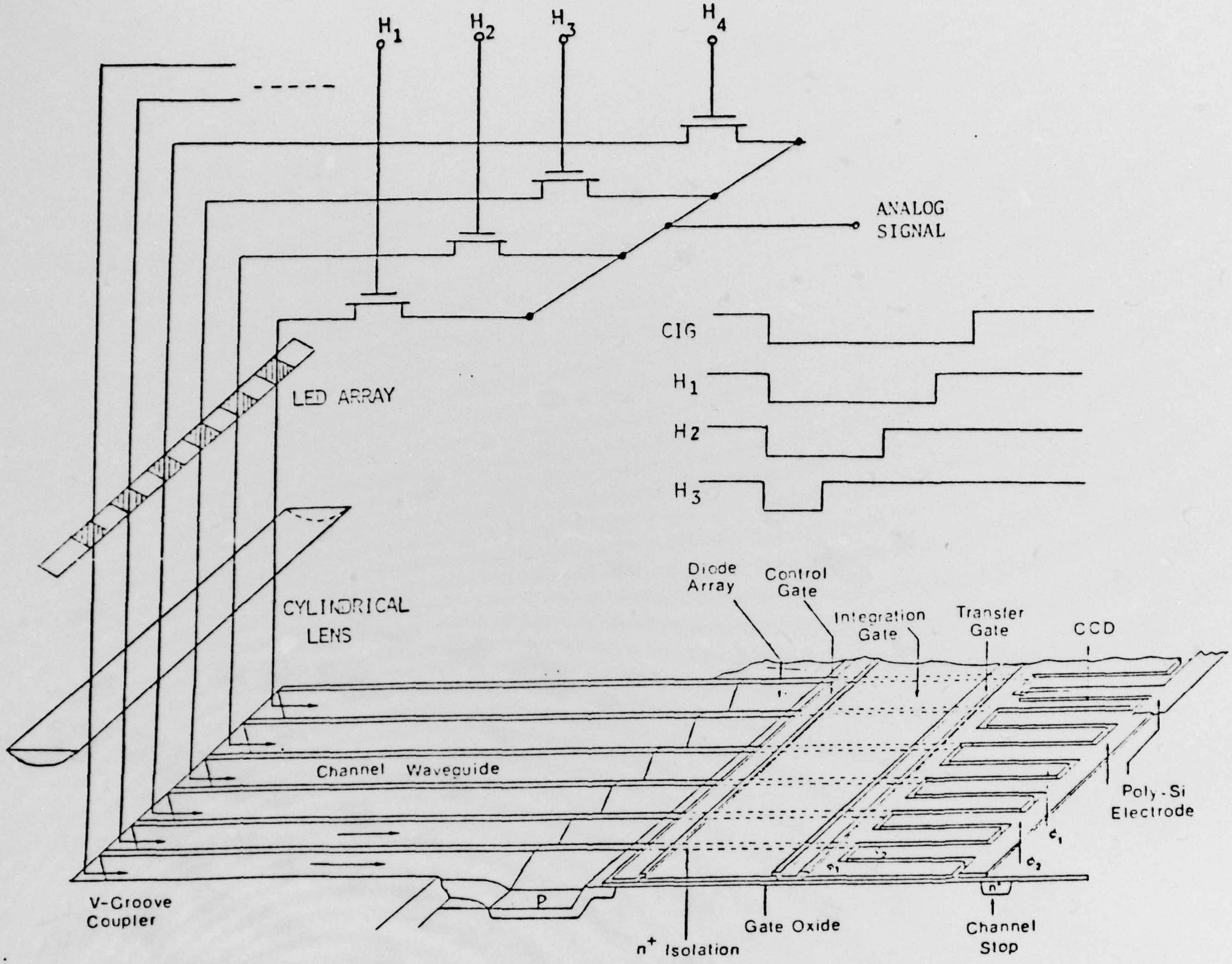

Figure 7 Schematic diagram of an integrated optical waveguide CCD transversal filter.